

SHINAGAWA TECHNICAL REPORT

耐火物研究におけるCAEの活用

CAE Applications for Research of Refractories

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要 旨

様々な分野の研究開発で使用されているCAE (FEM, CFD) 解析は、耐火物業界でも使用されている。本報では、当社が導入したFEM解析ソフト (MSC社 Marc) を用いて、取鍋の伝熱解析と拘束加熱下での熱応力解析を行った例と、CFDソフト (MSC社 scFLOW) を用いて連続鋳造のモールド内溶鋼流動とタンディッシュ内の介在物挙動の解析を行った例を報告する。伝熱計算ではカーボンニュートラルやSDGsの取り組みに役立ち、熱応力解析は損傷要因の推定を行い改善の方向性を知ることにつながる。溶鋼流動解析や介在物挙動解析では流れや動きを可視化して顧客製品品質の向上につながる。今後もCAE解析を積極的に活用し耐火物の更なる発展に貢献したい。

Abstract

CAE analysis is used for research and development in various fields, including the refractories industry. In this report, we present examples of analyses conducted using the software applications we have adopted. Two types of analysis software were utilized: thermal analyses of the steel ladle and thermal stress analyses of heating tests under constraints, which were carried out using Marc, and the flow analyses of molten steel inside the continuous casting mold and the analyses of the behavior of inclusions in the tundish, which were carried out using scFLOW. Thermal analyses contribute to carbon neutrality efforts and the achievement of the Sustainable Development Goals (SDGs), while thermal stress analyses help estimate the causes of damage and indicate directions for improvement. Analyses of molten steel flow and inclusion particle behavior can enable one to visualize the flow and motion, leading to improved quality of clients' products. We aim to contribute to the further development of refractories by actively utilizing CAE analyses.

1. 緒言

CAE (Computer Aided Engineering) は1960年代アメリカ航空宇宙局 (National Aeronautics and Space Administration: NASA) のために開発されたのが始まりであり、解析ソフトウェアが商用化されたのは1970年代のことである。1990年代以降PC、ソフトウェアの性能が飛躍的に向上したことで今では多様な業界の

1. Introduction

Computer-aided engineering (CAE) development began in the 1960s for the National Aeronautics and Space Administration (NASA) and was commercialized in the 1970s. After the 1990s, the performance of computer hardware and software improved dramatically, leading to the widespread use of CAE in research and development across

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Table 1 List of CAE software owned by our company and simulation cases

CAE	Software	Simulation cases	
FEM	Marc	Heat transfer analysis	Heat loss analysis of the ladle
		Stress analysis	Reproduction of three-point bending test
		Thermal stress analysis	Thermal stress analysis of the plate
CFD	PHOENICS scFLOW Fluent	Single-phase flow analysis	Reproduction of molten steel flow in the mold
		Multiphase flow analysis	Slag-metal separation in the blast furnace trough
		Particle tracking analysis	Inclusion behavior analysis in the tundish

研究開発に使用されるようになった。耐火物業界では1980年頃から利用され始め有限要素法 (Finite Element Method: 以下FEM)¹⁾を用いた熱応力解析, 数値流体力学 (Computational Fluid Dynamics: 以下CFD)^{2, 3)}を用いた熱流体解析の報告事例が多数ある。FEMの解析報告では例えば若杉ら⁴⁾はSVプレートの固定方法と亀裂発生の関係性を構造解析及び実験によって明らかにした。内田ら⁵⁾は転炉のライニング構造によるレンガの損傷状況を2次元軸対称モデルにて再現している。CFD利用例としては溝部ら⁶⁾がエネルギー損失を抑え介在物(アルミナなど)付着を抑制する浸漬ノズルの吐出孔形状を提案している。またHacklら⁷⁾はタンディッシュに設置するボックス堰の形状差によるタンディッシュ内溶鋼流動を解析し水モデル実験結果と比較をしている。

また、近年カーボンニュートラルやSDGsの観点から、耐火物業界では低熱伝導による熱ロス低減について積極的に具体的数値による削減効果を示すことが望ましい。このような実測定が困難な場合においてもCAEを活用すれば削減効果のシミュレーションは可能である。

Table 1に当社のCAEソフトについて整理する。解析には専用のソフトウェアが必要であるが当社では1985年にFEM解析ソフトであるMSC社のMarcを導入した⁸⁾。CFDについては2012年にCHAM社のPHOENICSを導入し耐火物の形状検討⁹⁾で本格的に活用し始めた。近年新たにMSC社 scFLOW, Ansys社 Fluentを導入したことでより複雑な物理現象の再現が可能となっている。

本報ではCAE解析例として取鍋の伝熱解析, 拘束加熱実験での熱応力解析, モールド内溶鋼流動解析, タンディッシュ内の介在物挙動解析を紹介する。

2. 耐火物のCAE手法

2.1 伝熱解析・熱応力解析

高温で使用され様々な応力が発生する耐火物の解析にお

various fields. For studies on refractories, CAE began to be used around 1980, and many results have been reported regarding thermal stress analyses using the finite element method (FEM)¹⁾ and thermal fluid analyses, which are specifically categorized under computational fluid dynamics (CFD)^{2, 3)}. As examples of stress analyses, Sugita et al. demonstrated the relationship between the fixing method and cracking behavior of SV plates through experiments and structural analyses⁴⁾. Uchida et al. simulated the dependence of the damage profiles of the converter on lining structures through calculations using two-dimensional axisymmetric models⁵⁾. As examples of CFD studies, Watabe et al. proposed a designed outlet hole in the submerged entrance nozzles (SEN) to reduce the adherence of inclusions⁶⁾. Hackl et al. reported analyses of changes in the molten steel flow in the tundish due to differences in the turbulence inhibitor, along with validations comparing the results of simulations and water model examinations⁷⁾.

Recently, at the point of achievement of carbon neutral for Sustainable Development Goals (SDGs), it is required to quantitatively demonstrate the thermal loss reduction effect of the refractories products. Utilizing CAE allows us to estimate values that are difficult to measure directly.

The CAE software applications we are using are shown in Table 1. The complex analyses require such sophisticated software. In 1985, we adopted Marc, a FEM analysis software application developed by MARC Analysis Research Corporation (currently known as MSC Software), and began utilizing CAE. In the case of CFD, we began utilizing PHOENIX, created by CHAM, for the design of bricks used in continuous casting in 2012⁹⁾. Nowadays, we have newly adopted scFLOW (MSC Software) and Fluent (Ansys) to reproduce more complex behaviors, specifically three-dimensional models, multi-phase

いて伝熱解析，応力解析またそれらを組み合わせた熱応力解析は耐火物のCAEとして検討がなされてきた。これらの手法として主にFEM解析が用いられている。FEM解析は解析対象を小さな要素に分割し要素ごとに微分方程式を近似的に解く手法である。解析対象にかかる変位，荷重などを境界条件として設定し解析対象の変形，発生応力，ひずみなどを評価することができる。耐火物の場合熱負荷による変形がほとんどであるため，先に伝熱解析を実施したのち伝熱解析結果を条件設定に組み込み応力解析を実施する。

3章でFEM解析ソフトであるMarcを用いた計算結果例として，取鍋の伝熱解析と拘束加熱下での熱応力解析を行った結果を示す。

2. 2 流体解析

溶鋼などの高温流体を取り扱う耐火物において流体流動を可視化し耐火物形状を最適化することは顧客の製品品質向上につながる。以前から手法としてCFD解析が用いられてきたが，流体の非定常性を再現するにはスーパーコンピュータによる解析が必要な場合があった。コストの面から研究開発での使用は限定的であったが，ここ数年のPCの進歩により汎用ワークステーションPCでの解析が可能となり耐火物研究での活用も増加している。

CFD解析も流体領域を要素で分割し支配方程式を駆使し近似的に解を求める手法である。離散化の手法として差分法，有限体積法，有限要素法，粒子法などがあり解析事象に合わせて選択する。

4章でCFD解析ソフトであるscFLOWを用いた計算結果例として，連続鑄造のモールド内溶鋼流動とタンディッシュ内の介在物挙動の解析を行った結果を示す。

3. FEM解析

3. 1 取鍋の伝熱解析

ここでは熱解析の例として，電気炉製鋼プロセスを想定した取鍋の伝熱解析を示す。電気炉製鋼プロセスでは，電気炉から出鋼された溶鋼は取鍋に装入され，精錬工程を経て鑄造される。取鍋における熱放散はプロセス全体でも大きな割合を占め，SDGsの達成に向けて断熱設計の最適化が求められる。本項では，メタルラインを低熱伝導率の材質に変更することによる効果を，消費エネルギーとCO₂排出量の指標で試算した。

Fig.1に解析モデルを示す。電気炉製鋼プロセス用の容量70tの鍋を想定し，簡略化したモデルを作成した。シミュレーションではメタルラインの材質をカーボン含有で熱伝導率の高いアルミナ-マグネシア-カーボン(AMC)れんがから，カーボンを含まない低熱伝導率のアルミナ-マグネシ

and unsteady states.

In this report, we present examples of analyses, specifically the heat transfer analysis of the steel ladle, the thermal stress analysis of the heating test conducted under constraints, the flow analysis of molten steel in the molds, and the motion analysis of inclusion particles in the tundish.

2. CAE Methods for Refractories

2. 1 Thermal and stress analysis

Due to the high temperatures and various stresses experienced by refractories, thermal analysis, structural analysis, and thermal stress analysis—which integrates both thermal and structural aspects—have been actively studied as valuable CAE methods for the research and development of refractories. These analyses are mainly carried out through FEM. FEM is one of the numerical simulation methods that makes it possible to solve the differential equations of complex models by dividing the simulation object into small elements. We can obtain deformation, stress, temperature, and other simulation results by configuring material properties such as elasticity or thermal conductivity, along with boundary conditions like external forces or heat. In the case of stress simulations of refractories, the deformations are primarily caused by thermal stress; therefore, analyses are conducted using the results of previously performed thermal analyses as the conditions.

In Chapter 3, we will present the results of thermal simulations for the steel ladle and thermal stress simulations of the heating test conducted under constraints, using Marc, the FEM simulation software application, as examples.

2. 2 Fluid analysis

Visualization of flow is one of the most regarded topics since some kinds of the refractories deal with high temperature fluid such as molten steel and optimization of the shape design of the refractories leads to improvements in the quality of steel products. For unsteady state simulations, huge computer systems were required therefore the fluid analysis have had limited use due to cost factors. However, with the recent remarkable advances in computer technology, it has become possible to perform CFD analyses with standard workstation PCs and so utilization of CFD is developing.

CFD also provides simulation by dividing the object into elements and solving the relational equations among elements. There are various

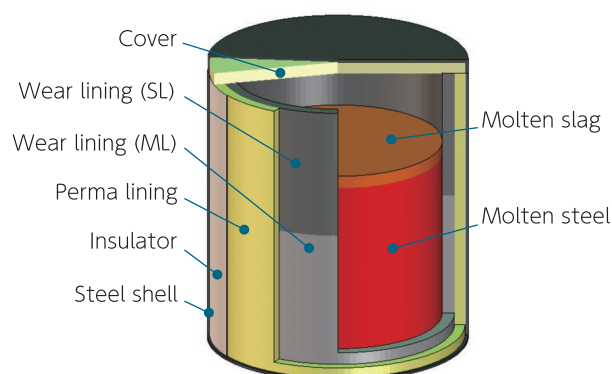


Fig. 1 Model of 70 t ladle for thermal simulation.

methods to discretize the model, for example, finite difference method, finite volume method, and particle hydrodynamics method, and it is necessary to choose the method that is suitable for the simulating phenomena.

In chapter 4, we present the results of flow simulations in the mold for continuous casting and motion simulations of inclusion particles in the tundish as examples of simulations conducted using scFLOW, CFD simulation software application.

3. Examples of Thermal and Stress Analysis

3. 1 Thermal analysis of steel ladle

In this section, we present the thermal simulation assuming the steel ladle in the electric arc furnace (EAF) based steel mill. In the EAF based steel mill, molten steel produced by EAF is inserted into the steel ladle and sent to the casting process after the refining process. The heat loss while the molten steel is in the steel ladle accounts for a significant portion

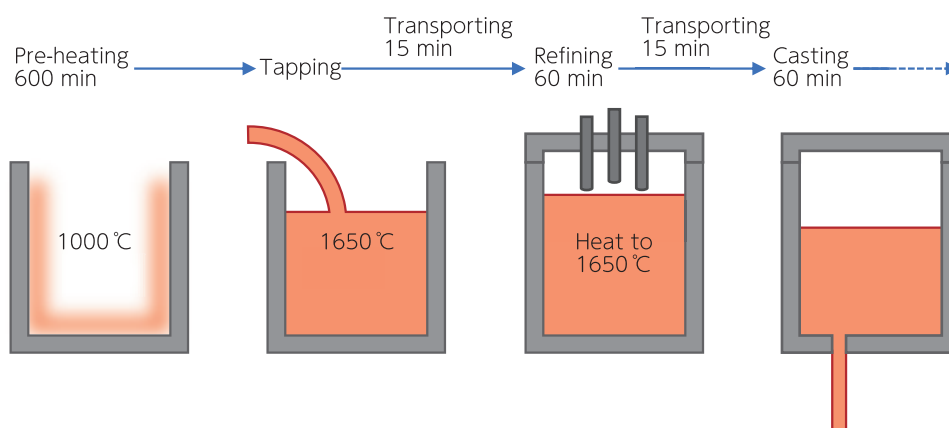


Fig. 2 Schematic image of ladle operation cycle for thermal simulation.

Table 2 Material properties of ML bricks for thermal simulation

		AMC brick	ALTIMA
Thermal conductivity / $\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$	200 °C	14	4.4
	600 °C	12	3.7
	800 °C	12	3.4
Specific heat capacity / $\text{J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$	200 °C	1.0	1.0
	600 °C	1.3	1.2
	800 °C	1.3	1.3
Bulk density / $\text{kg}\cdot\text{m}^{-3}$		3.3×10^3	3.4×10^3

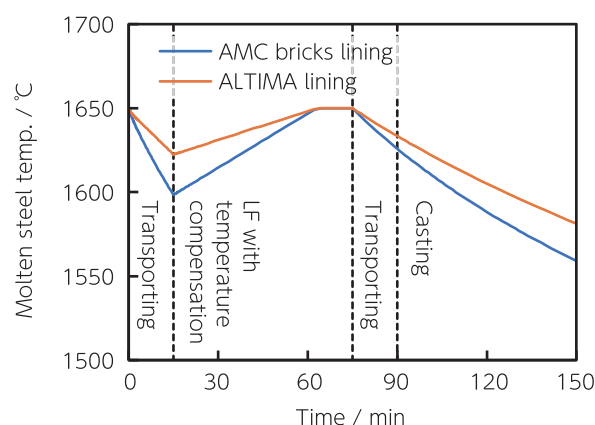


Fig. 3 Simulation results of average molten steel temperature variation during ladle operation cycle.

アレんがのALTIMA¹⁰⁻¹³⁾に変更した場合の比較を行った。シミュレーションに使用したれんがの熱的特性をTable 2に示す。なお、スラグラインにはマグネシア-カーボン質、永久張りにはアルミナ-シリカ質のれんが特性をそれぞれ共通で適用した。計算条件として与えた鍋の稼働サイクルをFig.2に示す。LFによる2次精錬時に温度補償として1650℃まで溶鋼を加熱する条件を温度指定で与え、この際に必要となる投入熱量を比較した。

受鋼後から casting 終了までの溶鋼温度時間変化をFig.3に示す。Table 2で示したようにALTIMAの熱伝導率はAMCの約1/4である。断熱性の高いれんがを配材することで溶鋼の温度低下を抑制できる効果が試算された。Fig.4に温度補償における熱量の消費内訳を示す。れんがの変更により主に耐火物ライニングへの熱の移動が低減され、全体として約40%のエネルギー消費の低減が見込まれた。また、アーク加熱による加熱効率¹⁴⁾を85%と仮定した場合の消費電力と基礎排出係数代替値¹⁵⁾を基に換算した昇温に係るCO₂排出量を併せて示した。

このようにFEM解析による伝熱計算は具体的な数値が算出可能で、CO₂排出量目標達成に向けたカーボンニュートラルやSDGsの取り組みの目安にすることができると考える。

3. 2 拘束加熱下の熱応力解析

次に熱応力解析の例として、拘束下加熱による亀裂試験^{16, 17)}の解析を示す。実炉使用において、耐火物は鉄皮や周辺部材によって拘束された状態で加熱され、内部に熱応力が生じる。応力が過剰になった場合に亀裂損傷につながるが、応力の方向や分布の空間的、時間的変化は複雑で、また実験的に観察することは難しい。本項では、実炉を模した条件での加熱試験を実施し、実験で発生した亀裂、発生応力の原因についてシミュレーションを利用した考察を

of the total losses in the whole process. Therefore, it is important to optimize the heat insulation design of the steel ladle to achieve the SDGs. We calculated the effect of switching the metal line material to the bricks with low thermal conductivity and presented the results in terms of energy consumption and CO₂ emission.

The model for thermal simulation is shown in Fig. 1. The schematic model of the 70 t steel ladle, assumed to be used in the EAF based steel mill, was prepared for the simulation. In the simulation, a comparison was made between the case where the material of the metal line was changed from carbon-containing high thermal conductivity alumina-magnesia-carbon (AMC) bricks to carbon-free low thermal conductivity alumina-magnesia bricks named ALTIMA¹⁰⁻¹³⁾. The thermal properties of these bricks are shown in Table 1. In addition, magnesia-carbon bricks and alumina-silica bricks were respectively applied to the slag line and permanent lining of each model. A schematic image of the ladle operation cycle for thermal simulation is shown in Fig. 2. The condition of heating the molten steel up to 1650℃ as temperature compensation was configured, and we evaluated the results by comparing the heat consumption required for this heating operation.

Fig. 3 shows the simulated temperature change of molten steel from the insertion of molten steel to the completion of casting. As shown in Table 2, the thermal conductivity of ALTIMA is 25 % of the value of AMC. The effect of the application of the low thermal conductivity bricks in reducing the temperature drop of the molten steel was visualized. The breakdowns of simulated heat consumption in temperature compensation process are shown in

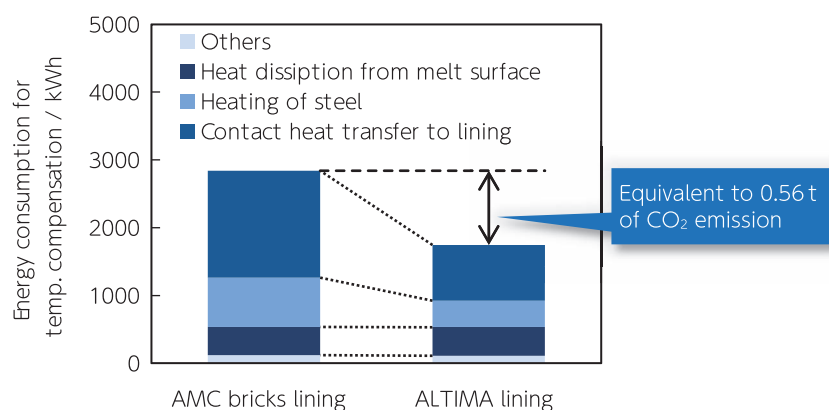


Fig. 4 Simulated energy consumption and equivalent reduction in CO₂ emission during temperature compensation in LF process.

実施した。

Fig.5に実験装置の模式図を示す。鉄皮内にれんがを円形に施工しれんが同士のせり合いによって拘束した状態で内面を加熱する。れんがの熱膨張差による亀裂の発生状況を確認する装置となっている。

試験後れんがが試料の断面をFig.6に示す。特徴的な損傷として水平な亀裂の発生が認められた。この実験結果の考察としてFEM解析による発生応力の検証を行った。Fig.7に解析モデル、Table 3に解析に使用したれんがの熱的特性を示す。周期対称性を利用したれんが1枚分のモデルとし、境界条件として内面を昇温する温度条件、上下方向の拘束として荷重の印可を設定した。

Fig.8にれんが断面における最大主応力のベクトル分布を示す。加熱面側内部に上下方向の引っ張り応力が分布しており実験で見られた亀裂の起点となったことが推測される。応力の方向から、加熱面から背面に向けて亀裂が進展すると考えられ、実験と一致する解析結果が得られた。亀裂発生要因調査として上下方向の拘束荷重を変化させた場合の結果をFig.9に示す。れんが内部の引っ張り応力が上下の拘束荷重に依存することが示され、円筒形状の軸方向の拘束が弱い場合に亀裂が発生する可能性が示唆された。

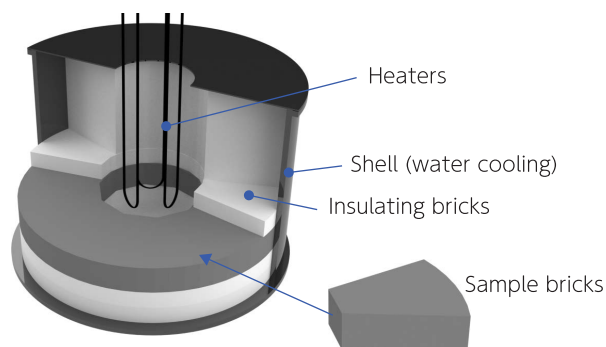


Fig. 5 Schematic image of facility for heating test under constraint.

Fig. 4. By replacing the bricks, the heat transfer to the lining was mainly reduced and the heat loss was reduced by a total of 40 %. Moreover, the reduced amount of CO₂ emitted by raising the temperature was also presented. The CO₂ emissions were estimated based on the electrical power calculated under the assumption of the arc heating efficiency of 85 %¹⁴⁾ and the coefficients indicated by Japanese Ministry of the Environment¹⁵⁾.

In summary, numerical thermal simulation can present quantitative estimation of energy consumption and be utilized as a benchmark for activity to achieve SDGs or carbon neutral.

3. 2 Stress analysis of heating test under constraints

In this section, we present the analysis of cracking tests under constrained heating conditions^{16,17)} as examples of thermal stress analysis. In actual use, refractories are constrained by outer shell or other surrounding structures while being heated, therefore thermal stress occurs in the refractories. Excessive stress causes cracking in the refractories, however, the spatial and temporal variations in the direction and magnitude of stress are complex and difficult to

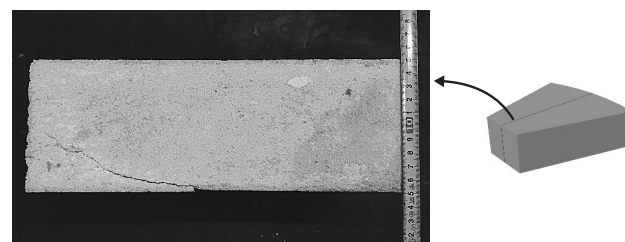


Fig. 6 Cross-sectional image of specimen after heating test under constraint.

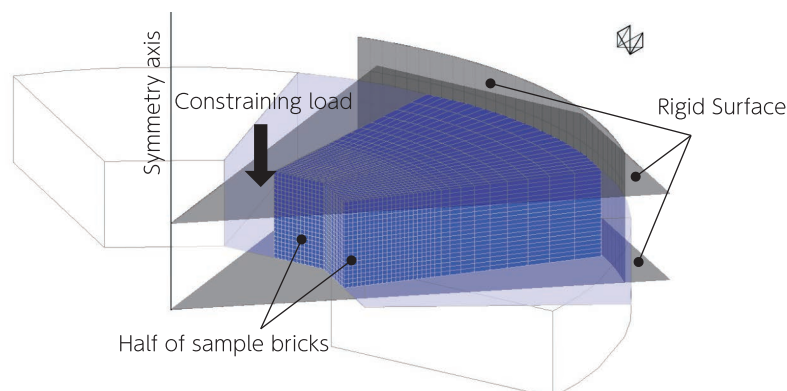


Fig. 7 Model for structural simulation of heating test under constraint.

Table 3 Material properties of sample brick for structural simulation of heating test

Bulk density / kg·m ⁻³	3.2×10 ³
Thermal expansion (1000 °C) / %	0.7
Modulus of elasticity (1000 °C) / GPa	30

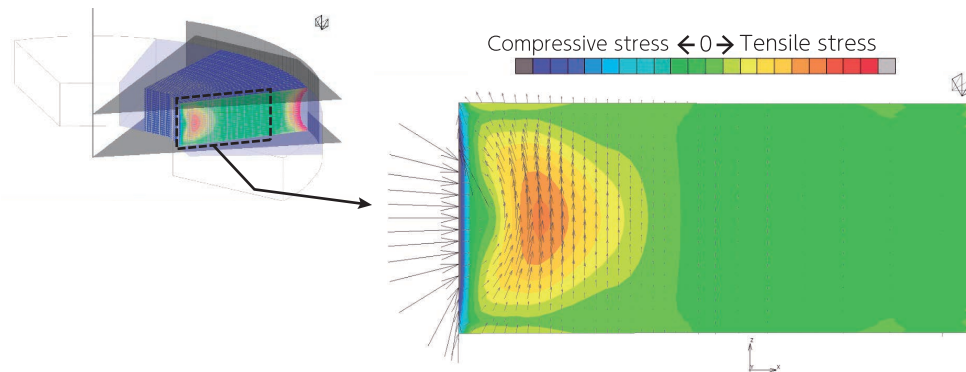


Fig. 8 Simulated distribution of maximum principal stress in cross section of sample for constraint heating test.

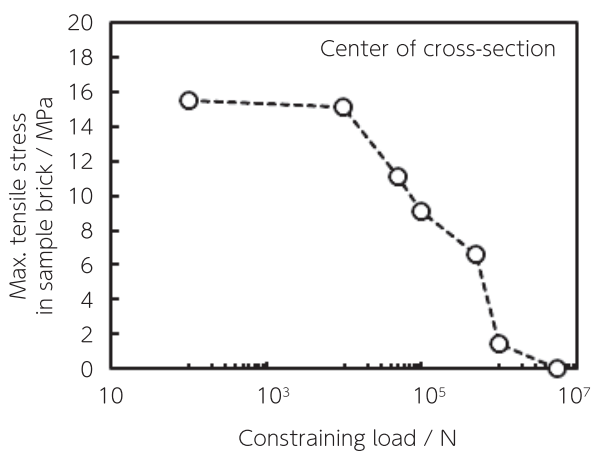


Fig. 9 Variation of simulated tensile stress in sample brick with changing constraining load.

このようにFEM解析による熱応力解析は、実験で再現が難しい特性や条件の影響、傾向を評価することができ、実験や実機で確認された損傷に対してその損傷要因の推定、材質や構造の改善の方向性について知見を得ることができる。

4. CFD解析事例

4.1 モールド内溶鋼流動

CFD解析例として浸漬ノズル形状差によるモールド内溶鋼流動解析結果を示す。モールド内溶鋼流動は安定した鑄片品質を維持するうえで極めて重要である。鋼種・鑄造条件により求められる溶鋼流動が異なるため浸漬ノズル形状は操業条件に合わせ設計している¹⁸⁾。これまでは実機スケールで水モデル実験を実施し検討していたがテストノズルの作成に時間・コストがかかること、また実験労力も大きいことから多形状の実施が困難であった。本項では2形状ノズルを用いて非定常解析を実施し溶鋼表面流速(メニス

observe experimentally. We will discuss the causes of cracks and stresses observed in the experiments, utilizing numerical simulations of the heating tests conducted under conditions that replicate actual furnace conditions.

A schematic image of the experimental furnace is shown in Fig. 5. The sample bricks are constrained by being tightly arranged in a circle inside the cylindrical steel shell, and the inner surface is heated by the electric heaters.

A cross section of one of the bricks after the heating test is shown in Fig. 6. A characteristic crack that propagated in the horizontal direction was found. We carried out thermal stress simulations to analyze these results. The model and thermal properties of the sample brick for simulations are shown in Fig. 7 and Table 3 respectively. The model was created using periodic symmetry for the range of one brick, which was defined as two halves of a brick. As the boundary conditions, the heat transfer on the inner and outer surfaces and the external load on the top surface constraining in the vertical direction were configured.

Fig. 8 shows the simulated vector distribution of the minimum principal value of stress on the cross section of the brick. There was tensile stress inside of the brick near the heated surface, and this stress was considered to cause the crack found on the sample brick after the experiment. The direction of the stress indicated that the crack would propagate from the heated side to the back side, and this simulation result was consistent with the experimental results. The results of the simulations carried out with changing the constraining load to investigate the factor of cracking are shown in Fig. 9. The stress distributed within the brick depended on the constraining load, and it was suggested that cracking can occur if the constraints in the axial

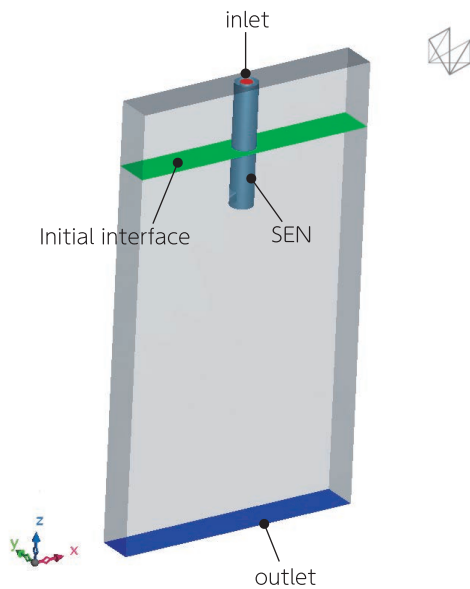


Fig. 10 Model for mold analysis.

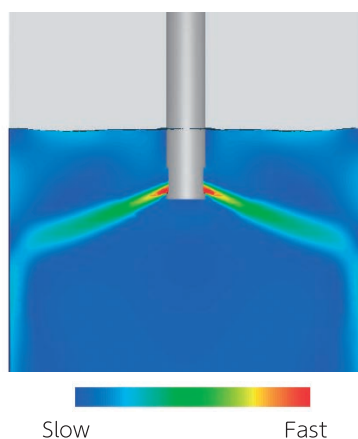


Fig. 11 Velocity distribution in mold.

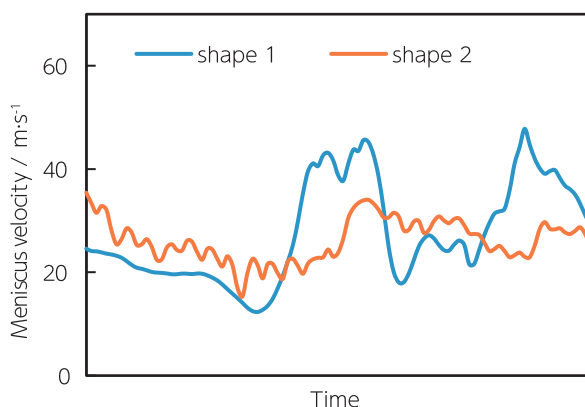


Fig. 12 Comparison of meniscus velocity.

direction of the cylindrical shape were insufficient.

Thermal stress analyses allow us to estimate the effects of material properties or conditions that are difficult to evaluate experimentally and provide suggestions for anticipating damage factors or implementing measures to improve materials and structures.

4. Examples of CFD Analysis

4. 1 Flow analysis of molten steel in mold

In this section, we present the results of the molten steel flow analyses in the continuous casting mold with different shapes of SEN. The flow of molten steel in the mold is crucial for ensuring the stable quality of steel products. The required flow of molten steel varies depending on the type of steel and the casting conditions; therefore, the shape of the SEN is designed to be optimized for the operational conditions¹⁸⁾. Generally, the designs of SEN have been evaluated through water model tests at actual scale; however, it has been challenging to conduct a variety of shapes due to the significant time and cost required to create the test SENs, as well as the considerable labor involved in the experiments. In this study, we conducted unsteady flow simulations using two different SEN shapes and compared the time dependence of the flow velocity at the surface of molten steel (i.e., meniscus velocity). The two SENs were identified as shape 1 and shape 2, with shape 2 featuring a larger angle for its downward-facing outlet port, resulting in a more downward flow.

The model for simulating the flow of molten steel in the mold is shown in Fig. 10. The upper end of the SEN bore was set as the inlet and configured with the throughput as the boundary condition. The bottom section of the mold was set as the outlet, where a flow rate was set to be equal to that of the inlet, so that the conditions of the actual casting could be reproduced. The contour plots of the simulated flow velocity results are shown in Fig. 11. The simulated results can be shown as animations, allowing for the visualization of the time-dependent changes in the flow. The numerical data of time-dependent changes in the meniscus velocities are shown in Fig. 12. The average velocity of both models was nearly the same at $0.3 \text{ m}\cdot\text{s}^{-1}$, with no significant differences observed. However, when comparing the variation of velocity, it was found that shape 1 showed a larger fluctuation in flow velocity. On the other hand, it was suggested that shape 2 allows for

カス流速)の時間変化を比較した。用いたノズルはshape1と2とし, shape2の方が下向き吐出孔角度が大きく吐出流が下向きとなる形状である。

Fig.10にモールド内溶鋼流動解析モデルを示す。浸漬ノズル上部内径をinletとし, 解析条件のスループットを設定する。モールド底面をoutletとし同量の流量を引き抜くことで実機を模した条件設定となる。流速コンター図をFig.11に示す。解析結果を動画で確認し, 時間変化に伴う変動を視覚的に確認できる。数値データとしてメニスカス流速の時間変化を比較した例をFig.12に示す。平均流速は $0.3\text{m}\cdot\text{s}^{-1}$ 前後と大きな差はみられないが, 時間変化を比較するとshape1は流速の変動幅が大きいことが判る。一方shape2は流速がほぼ一定であり安定したモールド内流動を得ることができると推測される。

このようにCFDを利用することで, 実機形状のノズルを用いなくても実条件の流動解析ができ, 複数条件での比較が可能となる。また, 非定常計算を行うことで, 時間変化による変動の可視化が可能となる。

4. 2 タンディッシュ内介在物挙動

次にCFD解析の一つである粒子追跡法を用いた例を示す。タンディッシュの役割として溶鋼中の介在物除去が挙げられる。介在物の浮上時間を確保し除去効率を上げる目的で多種形状の堰を設置する手法が検討されている¹⁹⁾。本項では堰設置位置を変更し流出粒子数を比較した例を示す。

Fig.13に解析モデルを示す。図中のモデルをNo.1とし堰位置をストッパー側へ600mm移動したものをしたものをNo.2, 1200mm移動したものをNo.3とした。タンディッシュ内の溶鋼流動を先に解き, 流れが定常状態となった後にロングノズル内から介在物を模した粒子を投入した。粒子の設定条件はTable 4に示す。タンディッシュ上ノズル部にoutletを設け粒子投入後500秒の流出粒子数を調査した。

a more constant flow velocity and enables a more stable flow within the mold.

In conclusion, CFD allows for the evaluation of SEN design under conditions that reproduce the actual machine and enables the comparison of various conditions. Moreover, unsteady state simulations make it possible to visualize the time-dependent changes in flow fluctuations.

4. 2 Motion analysis of inclusions in tundish

In this section, as examples of the particle tracking method, we present the analyses of the tundish. The particle tracking method is a type of CFD analysis that is widely used for the analysis of multiphase flow. The tundish is the vessel where molten steel is placed before being poured into the molds in continuous casting machines. As one of the functions of the tundish, the removal of inclusions from molten steel can be mentioned. The importance of allowing inclusions to float by ensuring sufficient retaining time and improving the efficiency of their removal by constructing turbulence inhibitors or weirs¹⁹⁾ has been considered. In this study, we present the results of the simulations comparing the effects of weir position on the quantity of inclusion particles flowing into the casting mold.

Fig.13 shows one of the models for the simulations. The model shown in the figure was identified as No. 1. The positions of the weir for the other models were shifted from that of No. 1 toward the outlet side: the weir for model No. 2 was moved 600 mm, and for model No. 3, it was moved 1200 mm. At first, we conducted molten steel flow simulations inside the tundish. After the flow became steady, particles simulating inclusions were introduced into the tundish from the inlet on the ladle shroud, and particle tracking was initiated. The configured particle conditions are shown in Table 4.

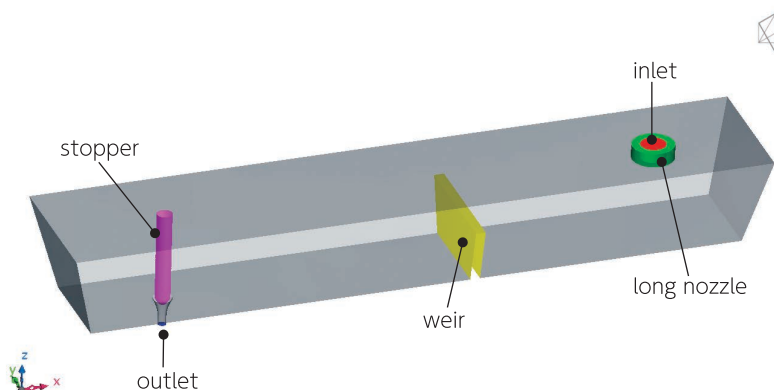


Fig. 13 Model for tundish analysis.

Table 4 Condition of particles

Bulk density / $\text{kg}\cdot\text{m}^{-3}$	2.5×10^3
Particle size / μm	30
Number of inflow particles	100

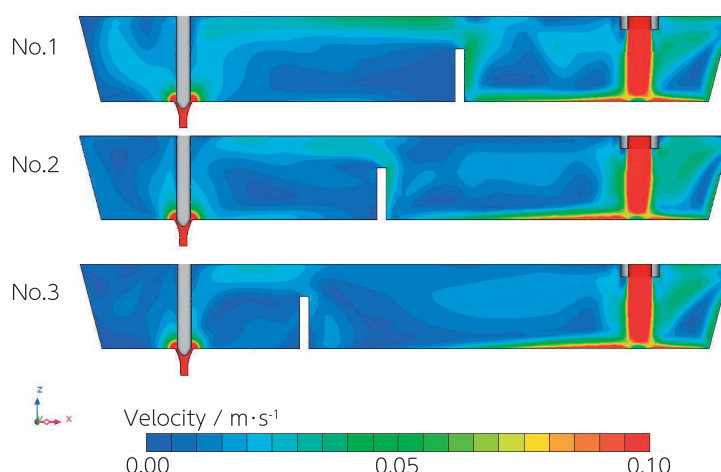


Fig. 14 Contours of velocity magnitude in x-z plane.

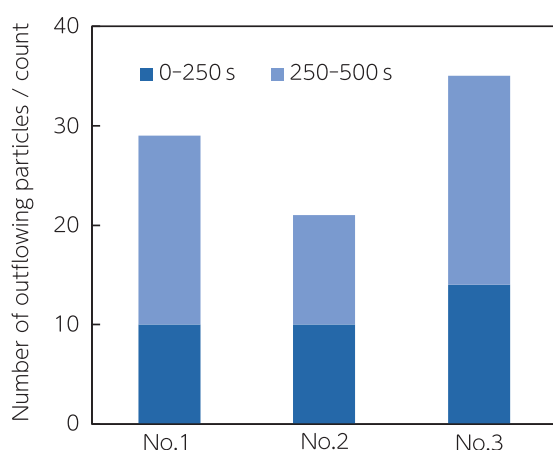


Fig. 15 Comparison of number of outflowing particles.

先に実施した定常解析の流速コンター図をFig.14に示す。ロングノズルに堰に近いほど堰を乗り越える流速が速くoutletへ向かう流速も速い傾向がみられる。速い流速に粒子が追従し移動すると仮定した場合No.1, No.2, No.3の順に流出粒子数は多いと推測される。次に粒子を投入し500秒間に流出した粒子数をFig.15に示す。250秒までの流出粒子数は各堰配置位置に大きな差がみられないものの、250-500秒間ではNo.2の流出粒子数がNo.1, No.3と比べて低減し、総流出粒子数はNo.2が最も少なかった。流出粒子数500秒時の粒子の位置と粒子軌跡をFig.16に示す。堰から下流域に着目するとNo.2はNo.1,3と比較しタンディッシュ底部やストッパー先端付近の軌跡が少ない傾向がみられた。流体の流れと粒子の挙動は必ずしも一致しないことが上記の解析結果からうかがえる。

このように流体の流れだけでは判断が難しいマイクロ

The results were evaluated based on the count of particles outflowing in 500 s from the outlets set on the bottom of the models, which simulate the upper nozzle in the actual machine.

The results of the molten steel flow simulations conducted initially are shown in Fig. 14 as contour plots of flow velocity. When the weir was closer to the ladle shroud, the flow velocity around the weir and the flow directed towards the outlet tended to be faster. If it was assumed that the particles follow the fast flow, the number of outflowing particles was expected to be greater in the order of No. 1, No. 2, and No. 3. Next, Fig. 15 shows the number of outflowing particles in the time span of 500 s during the particle tracking simulations. In the first half of the simulations (until 250 s), the results did not depend on the weir position. However, in the latter half (250-500 s), the number of outflowing particles in No. 2 was reduced compared to No. 1 and No. 3, resulting in the smallest total number of outflowing particles in No. 2. The positions and trajectories of the particles at 500 s are shown in Fig. 16. Focusing on the downstream areas of the weir for each model, fewer particle trajectories were observed at the bottom of the model and around the tip of the stopper in the No. 2 result, compared to those in No. 1 and No. 3. From these results, it can be inferred that the fluid flow and the particle motion do not always correspond with each other.

As demonstrated in these examples, it is possible to evaluate and compare the microscopic particle motions utilizing the particle tracking method, which is difficult to achieve with the flow analysis alone.

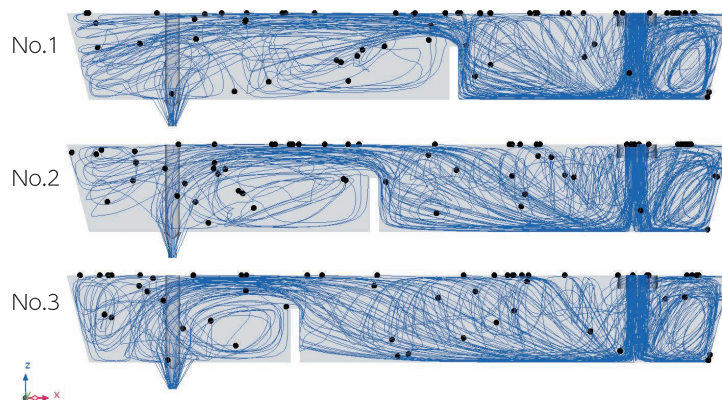


Fig. 16 Trajectory of particles after 500 s.

オーダーの粒子挙動も粒子法を用いることで比較、評価をすることが可能であり顧客の品質安定化に貢献できると考える。

5. 結言

本報では近年の当社でのCAE活用事例についていくつか紹介した。CAEは耐火物の耐用や鋼品質の改善、発生事象の要因解明といった活用方法以外に、カーボンニュートラルやSDGsへの検証にも有効活用できる。CAE解析は耐火物研究において今後さらに重要度が増すと考えられる。当社でも積極的に活用し耐火物のさらなる発展に貢献したい。

This approach can contribute to ensuring stable quality of clients' products.

5. Conclusion

In this report, we have presented recent examples of CAE utilizations in our work. CAE can be utilized not only to improve the durability of refractories and the quality of steel but also to investigate the factors behind various occurrences. Additionally, it is effective for assessing carbon neutrality and achieving the SDGs. The importance of CAE analysis is expected to increase further in the research of refractories. We aim to actively utilize CAE in order to contribute to the further development of refractories.

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